

High-heat-flux sensor calibration using black-body radiation

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Abstract. This paper deals with the radiative calibration aspects of high-heat-flux sensors using black-body radiation. In the last two years, several heat-flux sensors were calibrated up to 50 kW/m^2 using a 25 mm diameter aperture variable-temperature black body and a reference room-temperature electrical-substitution radiometer. Tests on a typical Schmidt-Boelter heat-flux sensor showed long-term repeatability of calibration is within $\pm 0.6\%$. Plans for extending the present calibration capability to 100 kW/m^2 are discussed.

1. Introduction

Heat-flux sensors are instruments used for measuring the heat-transfer rates at a surface due to thermal radiation or convection. The response of the sensors is proportional to the net heat-transfer rate at the sensing surface. Apart from their extensive use in heat-transfer research, heat-flux sensors, in particular radiant-type thermal radiometers, are standard calibration devices in fire-standard test methods [1].

At present, no US national standard exists to provide traceable heat-flux measurements for calibrating heat-flux sensors. Calibration methods used by sensor manufacturers depend on determinations of heat flux using pyrometric temperature measurements traceable to the National Institute of Standards and Technology (NIST). Calibration of the same sensors by different manufacturers or laboratories have shown variations as large as $\pm 8\%$ [2]. These variations in calibration mean that practical heat-transfer measurements using heat-flux sensors may well be substantially in error, and illustrate the need for traceable national standards for heat-flux sensor calibrations. To address this need, the Optical Technology Division (OTD) at the NIST is developing high-heat-flux sensor calibration methods traceable to radiometric standards.

The objective is to develop the capability to calibrate sensors up to 100 kW/m^2 . Fixed-point or variable-temperature black bodies form excellent sources of broadband radiant heat flux. To calibrate accurately high-heat-flux sensors, a large-aperture black body with variable-temperature capability is desirable. A large aperture results in higher radiation at a

given temperature and better uniformity of the heat-flux distribution across the sensor surface. Variable-temperature capability is useful for continuous change in heat-flux level at a fixed configuration between the black-body aperture and the sensor surface.

Two approaches are employed to calibrate heat-flux sensors using black bodies. The first approach, extensively used, relies on an ideal black-body environment [3]. The heat flux at the sensor surface is based on pyrometric measurement of black-body temperature and is calculated using black-body radiation equations. This approach is accurate when the distance between the black-body aperture and the sensor surface is large, and the view angle of the sensor is narrow. In the second method [4], a cavity-type radiometer which completely absorbs the incident radiation is used as a transfer standard to determine the heat flux at the sensor location. This approach has been used recently at the OTD to calibrate a number of heat-flux sensors. The calibration was made using the 25 mm variable temperature black body (VTBB) as a radiant source and a room-temperature electrical-substitution radiometer (ESR) as a transfer standard. This paper describes the types of heat-flux sensor tested, the experimental method used, and presents a summary of the results of calibration. Future plans to extend the capability are presented.

2. Types of heat-flux sensor

Several types of heat-flux sensor are used in practice, depending on the nature of the application [5]. The principle of operation of these sensors, however, depends on either the radial or axial flow of the incident heat flux on the sensing surface. The present calibration is mainly concerned with two popular types of gauge, Gardon and Schmidt-Boelter (Figure 1).

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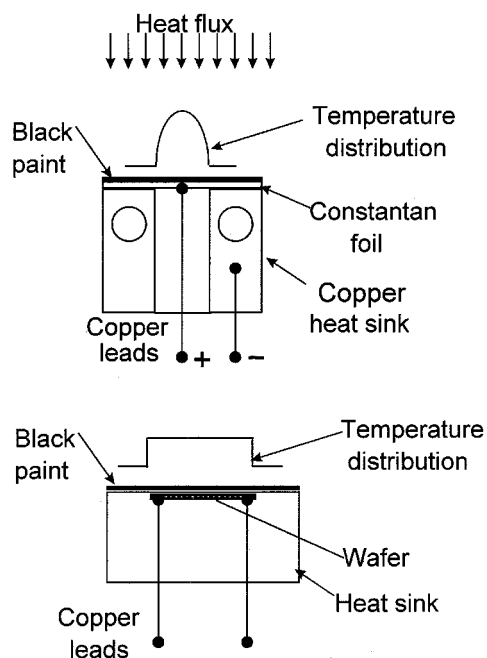


Figure 1. Gardon (above) and Schmidt-Boelter (below) heat-flux sensors. Characteristics of Gardon gauge: radial flow of heat in foil; parabolic temperature distribution; water-cooled (continuous use); body diameter 25 mm (typical). Characteristics of Schmidt-Boelter gauge: axial flow of heat (1-D); uniform temperature distribution; cooled or uncooled; body diameter 3 mm to 12 mm.

The Gardon gauge [6], named after the inventor, is an example of a radial-heat flow sensor. The sensor part is a circular foil (constantan) connected at the outer edge to a cooled copper heat sink. The heat flux incident on the sensor surface flows radially from the centre of the foil to the heat sink. This results in a parabolic temperature distribution across the sensing surface. The sensor works like a differential thermocouple whose output is proportional to the heat flux normal to the sensing surface.

The Schmidt-Boelter sensor works on the principle of axial one-dimensional heat flow. It measures the temperature difference across a thin, thermally insulating layer to determine the incident heat flux. Owing to the axial flow of heat, the temperature distribution across the sensing surface is uniform. The maximum body temperature is limited to about 200 °C. For applications involving continuous use, the sensor body is water-cooled. Reference [7] gives a detailed description of Schmidt-Boelter gauge operation.

From the calibration point of view, the different principles of operation of the two gauges are irrelevant. It is only necessary to expose the sensing surface to a uniform heat-flux distribution over an area much larger than the sensing surface.

3. Heat-flux transfer standard

Room-temperature cavity-type ESRs [8] are ideal for use as transfer standards to calibrate high-heat-flux

sensors. The incident photon flux is absorbed by the cavity to within a fraction of a percent. The electrical power required to produce the same temperature rise in the cavity as the incident flux is determined by measurement of voltage across and current through a precision-heating element embedded in the cavity. Considering the effective absorptivity of the cavity and other factors, the measurements by ESR are likely to be within 0.5% of the true value.

In this work, a Kendall radiometer with a range of 4.2 W is used as a transfer standard. The radiometer has an aperture area of 1 cm² and a field-of-view of 180°. The 1/e time constant is about 6 s for a step change in irradiance. For large changes in heat flux, it is necessary to allow about 60 s for stabilization before measurements are made. Considering the uncertainties in the use of heat-flux sensors, the accuracy of this radiometer (0.5%) is acceptable. To establish traceability and long-term repeatability, however, the ESR is calibrated [4] against a working standard detector calibrated in the NIST cryogenic radiometer [9].

4. Calibration of sensors in the 25 mm VTBB

Figure 2 shows the schematic arrangement of the experimental setup in the 25 mm VTBB. This is an electrically heated graphite-tube, twin-cavity, black-body furnace. The heated tube cavity diameter is 25 mm, and the heated section is 28.2 cm long with a centre partition 3 mm thick. An optical pyrometer measures the temperature by sensing radiation from one end of the furnace. A proportional-integral-differential (PID) controller regulates the power supply to maintain the furnace temperature to within ±0.1 K of the set value.

The heat-flux sensors to be calibrated and the reference radiometer are located at a fixed distance from the exit of the black body. The apparent emissivity of the radiating aperture of the furnace is 0.99. Figure 3 shows the measured nominal heat flux at two distances from the radiating aperture. At a distance of 2.5 cm from the aperture, the maximum heat flux is about 100 kW/m². This location is typically avoided since it results in a nonuniform distribution of the argon

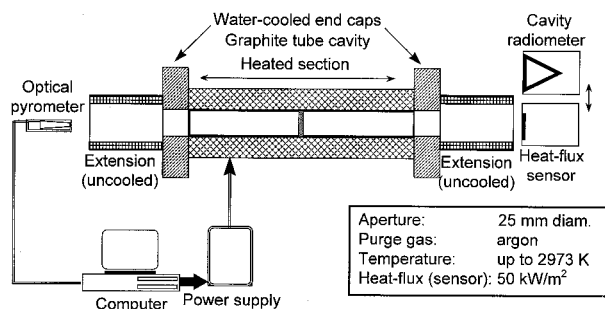


Figure 2. Schematic layout of the 25 mm variable-temperature black body.

purge gas flow in the cavity, reducing the life of the graphite tube and end caps. For routine calibration, the sensor is positioned at a distance of about 11 cm from the radiating aperture. The maximum heat flux at this location is approximately 50 kW/m² to 60 kW/m².

5. Results and discussion

One of the requirements in developing traceable calibrations is to establish long-term repeatability of the technique employed. Also, it is necessary to assess the effect of extraneous experimental factors on the gauge calibration. The long-term repeatability of the measurements in the VTBB is checked by calibrating a Schmidt-Boelter gauge at frequent intervals. The gauge is of miniature type, with a diameter of 5 mm and a length of 9 mm. The design heat-flux range is 110 kW/m². In the past year, six sets of calibrations have been made on this gauge. These calibrations included measurements of the sensor at different locations with respect to the black-body aperture, and over different black-body temperature ranges. Furthermore, after the first two sets of calibrations, the black-body setup was modified to improve temperature uniformity along the radiating cavity.

Figure 4 shows the measured response of the gauge in millivolts for different levels of incident heat flux in the range 0 kW/m² to 50 kW/m². All the calibrations show the expected linear response of the gauge, with regression factors of unity. Table 1 gives the gauge responsivity obtained from linear regression to the measured data. The agreement in responsivity is within approximately $\pm 0.6\%$ of the mean value from the six calibrations. The good repeatability of the data supports the long-term stability of the transfer standard ESR and the Schmidt-Boelter gauge, and validates the OTD measurement technique using the VTBB.

The transfer calibration technique described in this paper has certain advantages. It is based on direct

Table 1. Measured responsivity of a Schmidt-Boelter heat-flux sensor.

| Test No. | X/mm | Responsivity/ (mV/kW m ⁻²) | Deviation from mean/% |
|--------------------|------|---|--------------------------|
| 1 | 12.5 | 0.1189 | 0.00 |
| 2 | 62.5 | 0.1184 | -0.41 |
| 3 | 12.5 | 0.1190 | 0.14 |
| 4 | 12.5 | 0.1181 | -0.66 |
| 5 | 12.5 | 0.1191 | 0.24 |
| 6 | 12.5 | 0.1197 | 0.68 |
| Arithmetic mean | | 0.1189 | |
| Standard deviation | | 0.0006 | 0.48 |
| Standard error | | 0.0002 | 0.20 |

X: distance from VTBB exit to sensor.

measurements of the heat flux, rather than black-body temperature measurements. Hence, any departure of the black-body radiation from ideal conditions caused by extraneous experimental factors will have similar effects on both the reference radiometer and the sensor, and the calibration will not be affected. It is also possible to monitor the long-term stability of the reference radiometer with independent calibrations against a radiometric standard.

In the last two years, fourteen gauges have been calibrated using this transfer calibration technique. Table 2 lists the type and range of the gauges tested. The calibration range for all the gauges was about 50 kW/m². Figure 5 shows the percentage deviation from the NIST calibrations of the manufacturers' stated responsivities. The estimated uncertainty in the NIST calibrations is 1.5% to 2.0% with a coverage factor of 2 [10]. The repeatability of responsivity of the reference gauge calibrated over the same period as the other test gauges is within $\pm 0.6\%$. In some cases, the manufacturers' calibrations fall within this range. The good repeatability of the reference gauge suggests that the present calibration procedure is consistent. The differences of 3% to 6% observed between the NIST

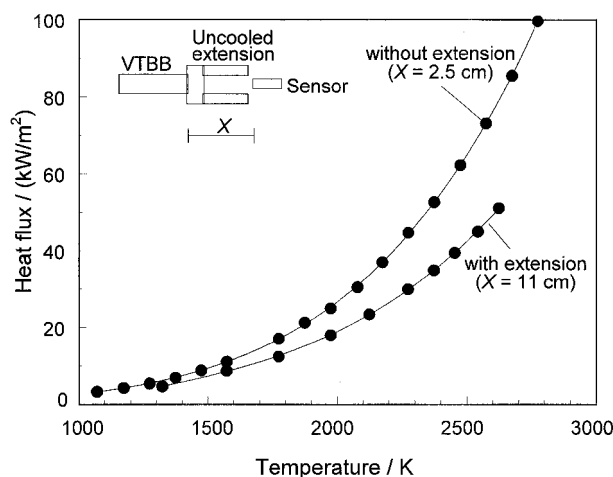


Figure 3. Measured heat flux in the 25 mm VTBB for two sensor positions from the black-body aperture.

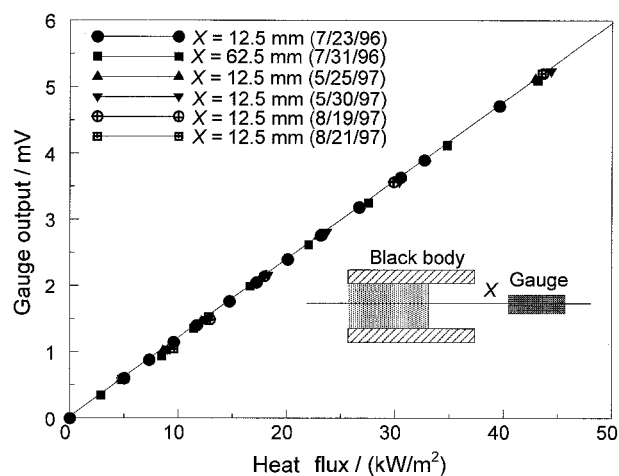


Figure 4. Results of repeat calibrations on a reference gauge.

Table 2. List of heat-flux sensors tested in the variable-temperature black body.

| Gauge type | Range/(kW/m ²) | No. |
|-----------------|----------------------------|-----|
| Schmidt-Boelter | 150 | 2 |
| Schmidt-Boelter | 56 | 9 |
| Schmidt-Boelter | 112 | 1 |
| Schmidt-Boelter | 70 | 1 |
| Gardon | 565 | 1 |

